NDE AND DESIGN — A UNIFIED LIFE-CYCLE ENGINEERING APPROACH

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INTRODUCTION

Unified life-cycle engineering (ULCE) is an approach that combines aspects of concurrent engineering, total quality management, and retirement-for-cause (RFC) strategies at the early design stage of components [1-3]. In order to implement ULCE approaches, inspectability, reliability, and the other "ilities" of Fig. 1 must be linked to areas such as quality assurance, life-cycle costs, and materials and processes in a comprehensive design environment.

NDE models can provide one of the key ingredients for the design environment of Fig. 1 because of their ability to be used for in-process control of important parameters in the manufacturing process, their role in process automation, and the ability of such models to consider in-service issues. Such models are also the foundation for other models involving reliability, life-cycle costs, etc.

Recently, significant progress has been made in establishing such NDE models as well as building the other links of Fig. 1 through the joint National Institute of Standards and Technology/Iowa State University/Northwestern University program in Integrated Design, NDE, and the Manufacturing Sciences. Here, we will describe the types of NDE and reliability models that have been built in the program and how they fit with the other ULCE elements shown in Fig. 1 to produce a new engineering technology for incorporating inspectability into a concurrent engineering design process.

NDE MEASUREMENT MODELS

One of the major accomplishments of the NIST/ISU/NU program has been the development of comprehensive models of NDE inspections and the integration of those models into the design environment. These models are all based on the fundamental physics of these NDE measurement processes, so we refer to the models as NDE measurement models.

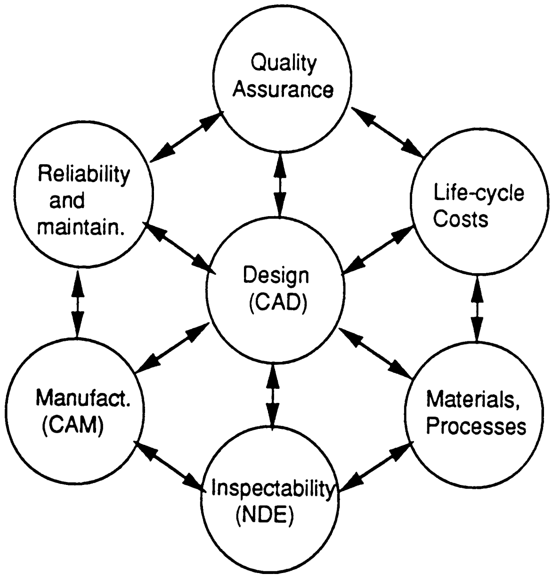

Fig. 1. A general Unified Life Cycle Engineering Environment.

For example, in ultrasonic NDE, the output of a typical measurement is in the form of an rf waveform (flaw signal) on an oscilloscope screen. Using a general form of the electromechanical reciprocity relations [4], this signal can be related to the velocity and stress fields in a component. To model these fields in realistic 3-D geometries requires the extensive use of models of sound generation, propagation, flaw scattering, and reception processes. Many of these models are numerically intensive and can require computational resources comparable to a large finite element calculation. Since either bulk waves or surface waves can be used in NDE testing and the physics of the inspection process is quite different in these two cases, we have actually implemented two ultrasonic models separately for these cases.

In eddy current testing, the reciprocal theorem can again be used to relate the measured complex electrical impedance signal of a flaw to the electromagnetic fields in a component [4]. As in the ultrasound case, detailed models are needed of the fields generated and their interaction with the part and the flaw. Currently, this modelling is done numerically using the Boundary Element technique

A measurement model has also been developed for a general x-ray inspection setup [4]. In this case the measurement is in the form of an image, usually captured on film. Thus, a model must be available to estimate the generation and the transmission of x-rays through a part as well as the image-forming process on the film. Implementation of this x-ray inspection model typically involves the use of ray tracing. For complex geometries, this tracing is done directly off the CAD solid model.

PROBABILITY OF DETECTION MODELS

Probability of detection for a component is, by definition, the ratio of the number of flaws detected by a given technique to the total number of flaws in the inspected components. POD is a well established measure of inspection performance that is directly related to important issues such as the frequency and quality of inspections, accept-reject criteria, cost of failure and repair, etc. [5]. Mathematically, POD can be expressed as the integral of a conditional probability. For example, in a 1-D model of the detection process:

$$\mathrm{POD}(a) \quad = \quad \int_{y_{th}}^{\infty} P(y \mid a)dy \tag{1}$$

where y is the amplitude of a flaw signal, a is the flaw size, and y_{th} is the smallest amplitude signal that will be considered (the experimental threshold set on the detecting equipment). $P(y \mid a)$ is the conditional probability that a flaw of size a will produce a signal of amplitude y. Typically, a POD(a) curve for a particular technique has a sigmoidal shape.

By extending the basic NDE measurement models described above to include models of the sources of variability in the measurement process (such as electronic noise, material variabilities, surface roughness, etc.) each of the three models have been used to simulate $P(y \mid a)$ and, hence, the resulting POD(a) curves. Details that go into those simulations can be found in [4]. In this manner the measurement models are turned into POD models that are directly useful for estimating inspectability of parts at the design stage. An example of the calculation of a POD(a) curve for a "pin" geometry that has been used as a test problem in the NIST/ISU/NU program [6] is shown in Fig. 2. It should be pointed out that POD calculations of this type are appropriate for automated systems and do not include many of the variabilities of human operators.

RELIABILITY MODEL

We have also developed an in-service reliability model that can be used to estimate, during the fatigue life of a part, when inspections should be made to keep the reliability of the part within "bounds". Specifically, the model describes the hazard rate as a function of time, t, with i inspections, $\lambda_i(t)$, versus the hazard rate without inspections, $\lambda_{NI}(t)$, through the relationship [7]:

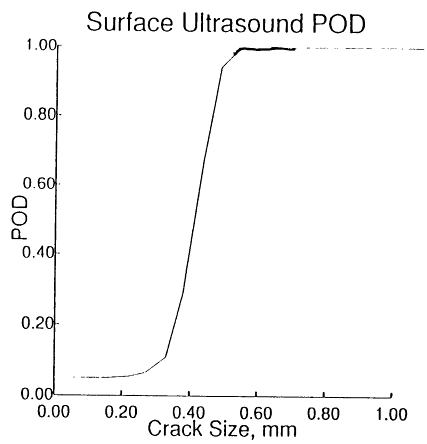

Fig. 2. The probability of detection versus flaw size using surface ultrasound for a flaw at the stress critical point.

$$\lambda_i(t) = \lambda_{NI}(t) \prod_{m=o}^{m=i} [1 - P_m(t)] \, (1 - F_{T,NI}(t))/(1 - F_{T,NI}(t) - P_{R,i}(t)) \tag{2}$$

where $F_{T,NI}(t)$ is the probability of failure of the part before time t in the absence of inspections, $P_{R,i}(t)$ is the probability of detection of the flaw at any one of the inspections before time t, given that the part has not failed before time t, and $P_m(t)$ is the probability of detection of a flaw at inspection m of a part that will fail at time t, or equivalently, $P_m(t) = POD(a_m(t))$ where $a_m(t)$ is the size of the crack at inspection m which will grow to the critical crack size, a_c, in time t.

The hazard rate function is a fundamental reliability quantity that can be used to determine a variety of important figures of merit with respect to reliability such as cumulative probability of failure, mean time between failure, etc. Thus, Eq. (2) give a methodology for calculating those important parameters. Also, if cost tradeoff information is available, Eq. (2) is an important input to life cycle cost estimates.

The basic inputs that are needed to calculate the hazard rate function are the POD(a) curves, the crack growth behavior a = a(t), or a = a(N), where N is the number of fatigue cycles, and the initial flaw size distribution, a_i, [8].

The POD curves are obtained, for each NDE method separately, from the POD(a) calculations at the critical (high stress) points in a design. To obtain a(t), however, is more complex. First, information is needed from the stress analysis on $\Delta K(a)$, where ΔK is the stress intensity factor versus flaw size during fatigue as calculated at the critical point(s). From materials tests, basic fatigue crack growth behavior is obtained by a fitting of the two constants C and n in a standard Paris law relation,

$$da/dN \quad = \quad C\,[\Delta K(a)\,]^n \tag{3}$$

An integration of Eq. (3) then gives a(N) implicitly through

$$N = \int_{a_i}^{a} da/C\,[\Delta K(a)\,]^n \tag{4}$$

provided that the initial flaw size, a_i, is known. In the NIST/ISU/NU program, short crack growth fatigue data is being used to obtain this initial flaw size and some information about its distribution.

Using an assumed initial flaw size distribution, a calculated stress intensity versus flaw size curve, and a crack growth curve (versus flaw size), the hazard function versus time can be calculated, as shown in Fig. 3 for the "pin" geometry used in the NIST/ISU/NU program [6]. As expected, without inspections the hazard function grows monotonically if there are no inspections. If the part were inspected using surface waves, which produced the POD(a) curve shown in Fig. 2, then the hazard rate function, as calculated from Eq. (2) with three assumed inspections, has the form shown in Fig. 4. It is seen that each inspection produces a significant drop in the hazard rate, but the hazard function quickly returns to larger values until the next inspection. Thus, inspections would have to occur more frequently to keep the hazard rate function small. In this case, therefore, it seems likely that reliability could be more easily improved by changing the pin material so that the crack growth curves are less steep and fewer inspections would be required.

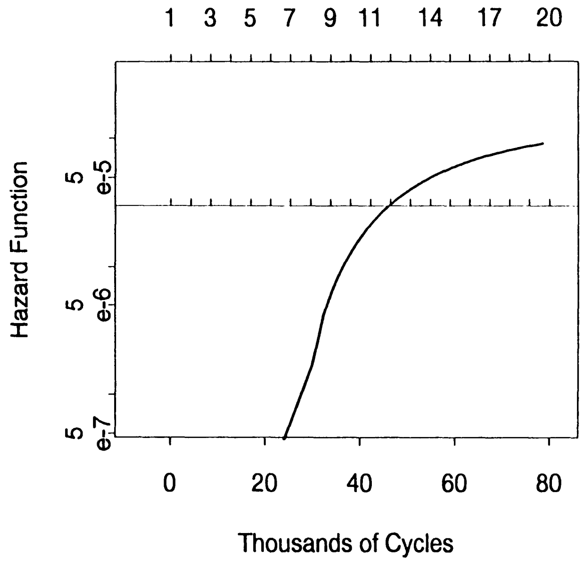

Fig. 3. Hazard function versus number of cycles with no inspections. Potential inspection times shown as integers 1-20 on top of the axis.

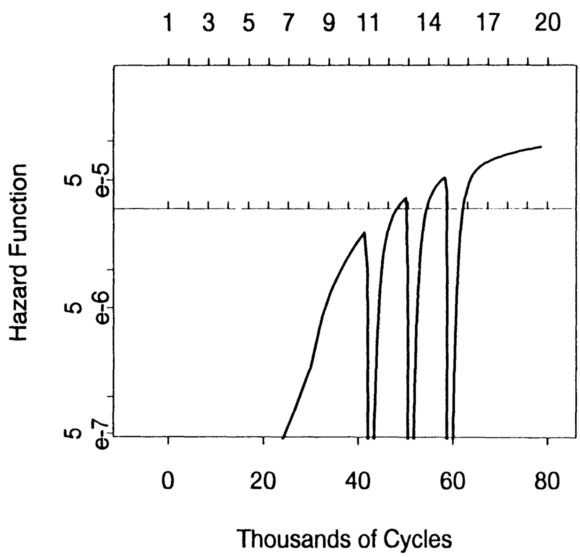

Fig. 4. Hazard function versus number of cycles with ultrasonic surface wave inspections of the stress critical point at times 11, 13, 15.

OTHER ELEMENTS OF THE CAD/ULCE DESIGN ENVIRONMENT

We have described the inspectability (POD) and reliability models that we have developed in the NIST/ISU/NU program and gave an example of how these models can be combined to consider in-service inspection issues. These models have been interfaced to a typical commercial CAD system (the I-deas package of SDRC Corp.) to illustrate how inspectability and reliability issues can be incorporated into even the very early design stage before parts are available. We have also built a number of supporting tools to assist a design team in this extended design environment. These include graphical design/communication user interfaces, experimental design and neural net based tools [9], [10] for making design change decisions, and distributed computing tools to allow the more rapid calculation of the effects of design changes. Our extended CAD/ULCE environment also includes NDE testing stations for ultrasonics, x-rays, and eddy currents. Thus, once a recommended design and an inspection set-up are available, this information can be down-loaded to the inspection stations and implemented on the actual parts when they become available from manufacturing.

CONCLUSIONS

We have described elements of a design environment that includes CAD, stress and materials analysis, inspectability estimates, and reliability calculations that are coupled together to form a new concurrent engineering design technology.

This technology allows NDE, for the first time, to play a major quantitative role in the early design process and provides the means for including ULCE and RFC methodologies also at the very early stages. As this technology matures, it should also prove useful in other aspects of the design process, including enhanced CAD/CAM links, improved process control, etc. Thus, the technology described here is an important generic base for a significantly expanded concept of what constitutes a "complete" initial design.

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REFERENCES

1. Burte, H. M. and D. E. Chimenti, "Unified Life-Cycle Engineering: an Emerging Design Concept", Review of Progress in Quantitative Nondestructive Evaluation, Vol. 6A, D. O. Thompson and D. E. Chimenti, eds., Plenum Publishing Co., 1797-1809, 1987.
2. Forney, D. M., "Evolving Partnership for NDE in Materials Engineering and Extended Life Cycle Performance", Review of Progress in Quantitative Nondestructive Evaluation, Vol. 10A, D. O. Thompson and D. E. Chimenti, eds., Plenum Publishing Co. 13-33, 1991.
3. Annis, C. G., Van Wanderham, M. C. Harris, J. A. and D. L. Sims, "Gas Turbine Engine Disk Retirement-for Cause: An Application of Fracture Mechanics and NDE", Trans. ASME, Journ. Eng. for Power, Vol. 103, 198-200, 1981.
4. Gray, J. N., Gray, T. A., Nakagawa, N., and R. B. Thompson, "Models for Predicting NDE Reliability", Metals Handbook, Vol. 17, 9th Ed., ASM International, 702-715, 1989.
5. Rummel, W. D., "Considerations for Quantitative NDE and NDE Reliability Improvement", Review of Progress in Quantitative Nondestructive Evaluation, Vol. 2A, D. O. Thompson and D. E. Chimenti, eds., Plenum Publishing Co., 19-35, 1983.
6. Schmerr, L. W. and D. O. Thompson, "Incorporating inspectability into design: the new role of NDE in concurrent engineering," First ASME/NDE Eng. Div. Topical Conf. on "NDE's role in concurrent engineering," San Antonio, Texas, April 21-23, 1992.
7. Garrigoux, C., "A Reliability Model for Planning In-Service Inspections of Components Subject to Fatigue Failure", unpublished manuscript, Iowa State University, 1990.

8. Harris, D. O. and E. Y. Lim, "Applications of a Probabilistic Fracture Mechanics Model to the Influence of In-Service Inspection on Structural Reliability", ASTM STP 798, J. M. Bloom and J. C. Ekvall, eds., Am. Soc. for Testing and Mat., 19-41, 1983.
9. Phadke, M. S. Quality Engineering Using Robust Design, Prentice Hall, Englewood Cliffs, N.J. 1989.
10. Schmerr, L. W., Nugen, S. and B. Forouraghi, "Planning Robust Design Experiments Using Neural Networks and Taguchi Methods", Intelligent Engineering Systems Through Artificial Neural Networks, Eds., C. H. Dagli, S. R. T. Kumara, Y. C. Shin, ASME Press, N.Y. 829-834, 1991.